

Dual Transition Edge Sensor Bolometer for Enhanced Dynamic Range

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Abstract

Broadband surveys at the millimeter and submillimeter wavelengths will require bolometers that can reach new limits of sensitivity and also operate under high background conditions. To address this need, we present results on a dual transition edge sensor (TES) device with two operating modes: one for low background, ultrasensitive detection and one for high background, enhanced dynamic range detection. The device consists of a detector element with two transition temperatures (T_c) of 0.25 and 0.51 K located on the same micromachined, thermally isolated membrane structure. It can be biased on either transition, and features phonon-limited noise performance at the lower T_c . We measure noise performance on the lower transition 7×10^{-18} W/rt(Hz) and the bias power on the upper transition of 12.5 pW, giving a factor of 10 enhancement of the dynamic range for the device. We discuss the biasable range of this type of device and present a design concept to optimize utility of the device.

Introduction

Space-based astrophysics at submillimeter and millimeter waves will rely on detectors with extremely low noise equivalent power ($\sim 10^{-18}$ W/rt(Hz)) such as that achievable with a transition edge sensor (TES) bolometer [1,2]. Many groups have demonstrated superconducting and semiconducting devices on thermally isolated structures with performance suitable for astrophysics. However, such devices have suffered from a relatively low bias power, which make them susceptible to saturation or degradation of sensitivity under high background conditions. The alternatives are to apply stringent limits on the throughput of the telescope at the focal plane or to devise a detector that maintains a suitable level of operation during high background observations. The ideal solution would not throw away photons and maintain photon noise limited detector performance.

We propose a high dynamic range device in which, on a single thermally isolated structure, detector and readout for low background limits are connected in series with a lower performance detector element, which operates under high background when the ultrasensitive detector is saturated. One technical path to enhancing dynamic range is modulation of the thermal conductance G , which controls the thermal transport between the detector element and the thermal bath. In many cases, the geometry of membrane thickness and aspect ratio of micromachined features set detector G . Concepts for intrinsic modulation of G are being pursued, for example, in the integrating bolometer work [3]. Here, we explore the modulation of dynamic G of the device with temperature. We present the design of a superconducting TES device exhibiting two distinct bias temperatures integrated into the same geometry and report on a successfully fabricated and tested device.

Superconducting TESs offer linear response over the entire biasable region of the transition, that is, the range of voltages over which the superconducting film is held with strong electrothermal feedback (ETF) in the narrow region between the superconducting and normal states of the detector element. Since the detector self-regulates at T_c , a voltage biased TES has the same bias power and hence G at any point on the transition. As show below, a device with two T_c s can be designed to have two G s and exhibit two distinct regions of bias voltage which have different bias powers. When biased at the low T_c , the high T_c portion is superconducting

and contributes no noise or power, enabling operation under low background conditions at the best achievable sensitivity of the device. Under high background conditions, the device remains biasable with strong ETF, albeit with a large parasitic resistance from the normal state of the low T_c device, such that the degradation in sensitivity can be well calibrated.

Performance of a dual transition device

We fabricated a dual T_c device by depositing Al and Ag films through a shadowmask onto a moveable mount holding a silicon substrate. The shadowmask is a silicon wafer with etched holes spaced several millimeters apart. It is mounted as an aperture plate directly in front of a 1 mm^2 silicon membrane ($1 \text{ }\mu\text{m}$ thick) with micromachined, thermally isolated legs, which can be manipulated in vacuum to deposit a chosen feature through the mask and onto the Si. A small ($50 \times 100 \text{ }\mu\text{m}^2$) Al/Ag proximity bilayer is deposited through two apertures such that the Ag film completely covers the Al film, ensuring normal metal boundary conditions in the superconducting element. A larger aperture is used to cover a fraction of the first bilayer with thicker Ag so that, for this device design, the dual T_c is exhibited by two segments of the same Al film. Then AlO_x is deposited (e-beam Al in 5×10^{-6} torr background pressure of O_2) on the legs to create contacts between the bilayer and frame of the chip. These leads are both resistive in the normal state ($>10 \text{ }\Omega/\text{sq}$) and high T_c ($\sim 2.5 \text{ K}$), ensuring that the leads make a negligible contribution to G at sub-Kelvin temperatures.

To obtain the current-voltage characteristic of the TES, the current through a shunt resistor in parallel with the TES is varied, generating a known voltage bias across the detector element. The current through the detector is then read out with a two-stage SQUID in which the first stage input coil is in series with the detector element in a superconducting loop. The resistance versus temperature is measured by noise thermometry at zero bias with the same SQUID amplifiers, which are impedance matched to have much lower input current noise than the Johnson noise of the detector element in its normal state. The low frequency current noise reflects the sum of the detector, shunt, and parasitic resistances in the loop, and the detector is presumed to be the only temperature dependent resistance over the sub-Kelvin temperature range.

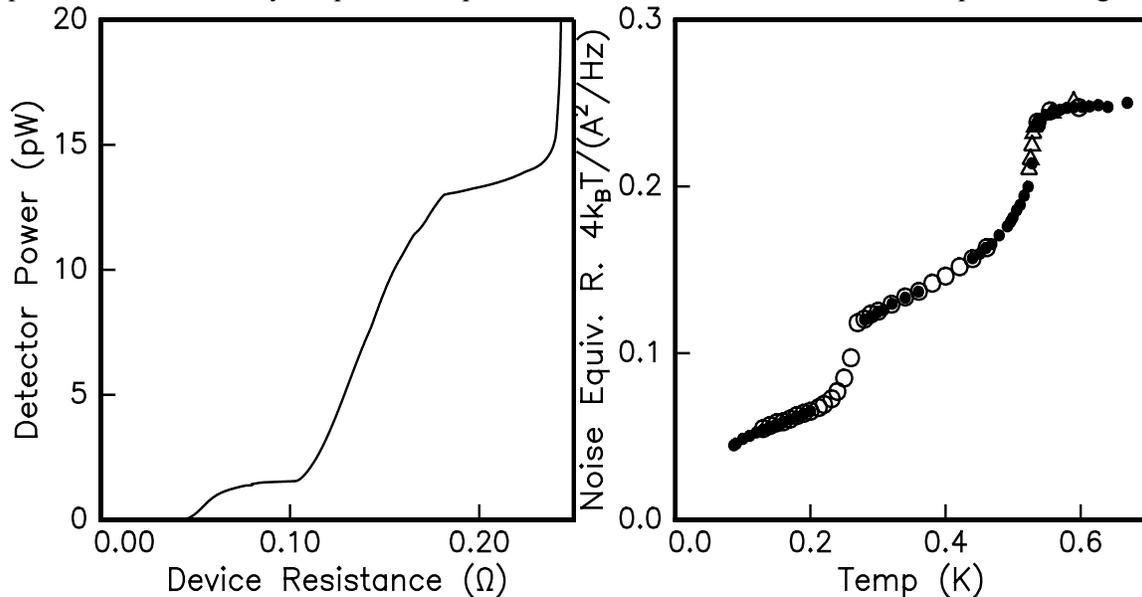


Figure 1(a) Power vs. resistance in a dual- T_c TES (b) Resistance vs. temperature of the same device

We show an I-V curve converted to detector bias power versus resistance in Fig. 1 (a). There are two regions of negative differential resistance in the IV that appear as flat power

regions of 1.2 and 12.5 pW, near 0.1 and 0.2 Ohms respectively, throughout which the detector exhibits strong electrothermal feedback. This factor of roughly ten in bias power constitutes the increase in dynamic range for this device, defined in terms of the total power throughput to the focal plane required to saturate the detector. In between these relatively flat regions is a sloping current-biased region in which the power in the detector keeps it on the upper transition but the parasitic resistance in the circuit prevents strong ETF because the detector is not voltage biased. The slight slope to the upper biasable region is also attributed to the parasitic, which perhaps varies as a function of bias voltage for this device. The base temperature for the thermal bath is regulated at 100 mK for the IV characteristic and the noise measurements presented in Fig. 2. The structure in the IV is corroborated by measurements of the resistance versus temperature curve for the device, shown in Fig 1(b). The RT curve exhibits two distinct sharp drops at 0.51 and 0.25 K and film resistance above each drop that corresponds to the resistance at the top of the flat power regions in the IV curve. It also shows a gradual resistance decrease in between the two sharp drops, likely a consequence of the method of fabrication, and a substantial parasitic resistance in the loop at the lowest temperatures.

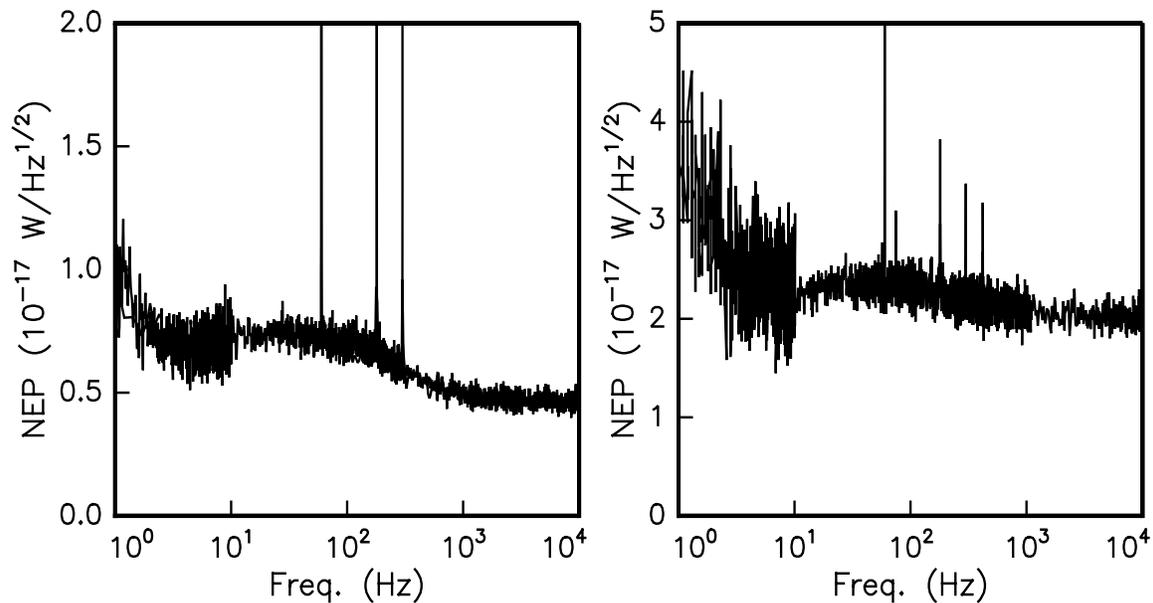


Figure 2(a) Noise measured in a dual- T_c device biased on the lower T_c (b) Noised measured at the high T_c .

We have taken noise measurements while the detector is biased at each T_c that are shown in Figs. 2(a) (low T_c) and 2(b) (high T_c). The current noise in the SQUID is measured and multiplied by the voltage at which the detector is biased. The low T_c device noise shows phonon-limited performance between 1-300 Hz and rolls off to the Johnson noise of the device at frequencies above the signal band. The measured value of 7×10^{-18} W/rt(Hz) is in good agreement with the theoretical limit $(2k_B T_c^2 G)^{1/2}$ that is predicted for strong ETF. The high T_c device noise shows excess noise in and out of the signal band but, measure at 2.3×10^{-17} W/rt(Hz), is still within a factor of two of the phonon-noise limit. The heat capacity of Si is comparable to that of the detector element at the high T_c and plays a role in this noise degradation [4].

Device design for enhanced dynamic range

We have shown that placing a well-thermalized superconductor of similar heat capacity in series with the detector element does not affect the performance of an ultrasensitive TES bolometer. However, it is apparent from Fig. 1 that the challenging part of the dual T_c detector is

designing a high T_c detector element that is biasable (i.e. at voltages where ETF is exhibited) over the largest possible range. A dual transition device can be implemented in several different ways including the series arrangement presented here in which a single element exhibits two T_c s, two separate sensors also connected in series, or independently biased detector elements on the same thermally isolated membrane. We first discuss the device with two detector elements wired in series.

The range of the biasable region on the high T_c device is determined by the size of the current-biased region in which the detector bias resistance is comparable to the sum of the normal state of the low T_c device (R_{l0}), shunt, and parasitic resistances. A device in which $R_{l0} \sim R_{hi}/4$ would provide a substantial biasable region for the higher T_c . Since a current-biased region of some extent is difficult to avoid, saturating the low T_c sensor with signal power may drive the device into a region that is difficult to calibrate quickly. Thus, to implement a two T_c device, a resistive heater element should be integrated onto the bolometer membrane with separate leads to supply quiescent power to the device prior to saturating with signal. The bolometer can then be calibrated to operate in a region of strong ETF at high T_c without having to adjust the bias voltage of the detector. Similarly, two separate detector elements connected in series will exhibit the same behavior. The advantage to this method is that a cleaner RT curve can be achieved, although the longer thermalization times may result in non-optimal noise behavior.

Note that the series impedance always limits the biasable range at high T_c . It also potentially suppresses the noise margin of the SQUID. The SQUID, in each case, must be optimized for the multiplexing limit for the low T_c current noise. Matching the detector noise at the top of the two transitions (for this example $T_c(\text{low})/T_c(\text{high}) \sim 0.25$ when $R_{l0} = R_{hi}/4$) makes best use of the dynamic range of the SQUID.

Independent biasing appears to be the most straightforward method to two T_c s. However, it requires separate bias line wiring, which, unless connected in series on the frame of the chip can result in more complicated room temperature electronics. Also, disconnecting the detector elements necessitates thermalization of their electron temperatures through the membrane. Either effect can lead to complicated transients and unwanted time constants in the detector response. This arrangement does leave open the possibility that separate SQUIDS be used to optimize amplifier noise for both operation modes.

In conclusion, a dual- T_c transition edge sensor bolometer has been fabricated and tested. The device exhibits the theoretical phonon-noise limit biased at the low T_c and a factor of ten dynamic range enhancement when biased at the higher T_c .

References

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